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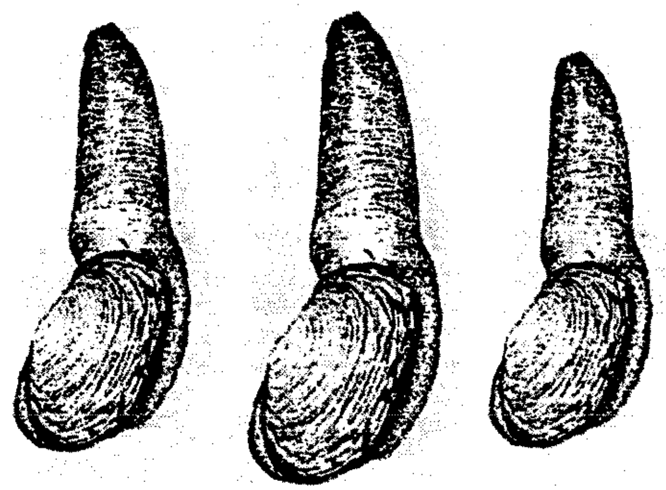
FINAL REPORT

The Transport and Fate of Suspended Sediment Plumes Associated with Commercial Geoduck Harvesting



Prepared for

State of Washington
Department of Natural Resources

APRIL 1992

EBASCO ENVIRONMENTAL
A Division of Ebasco Services Incorporated

THE TRANSPORT AND FATE OF SUSPENDED SEDIMENT PLUMES ASSOCIATED WITH COMMERCIAL GEODUCK HARVESTING

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1.0 INTRODUCTION

1.1 BACKGROUND

Commercial geoduck harvesting by divers using hand-held water jets has been shown to produce turbid plumes of suspended sediment down-current from the harvesting operation (Goodwin, 1978; Breen and Shields, 1983). Concerns raised in appeals to the Shoreline Hearings Board revolve around the issue of the transport and fate of such plumes, and the potential impacts on nearby aquatic communities and beaches due to deposition of material from the plumes.

These issues were addressed to some extent in the Environmental Impact Statement (EIS) for the Puget Sound Commercial Geoduck Fishery (State of Washington, 1985), hereafter referred to as the EIS. However, in light of the recent appeals, the State of Washington desires to explore existing information and to develop additional data relating to the transport and fate of fine particulate materials that may be placed into suspension during geoduck harvesting.

This report presents the results of a study designed to assess, and where possible, expand the existing knowledge base with regard to the physical processes that govern the transport and fate of such material. Biological impacts associated with geoduck harvesting are being addressed in a separate study.

1.2 OBJECTIVES

The general objectives of this study were threefold:

1) Provide an independent technical review of the EIS with respect to physical processes, in light of the current state of knowledge regarding such processes.

2) Collect additional data to extend the existing knowledge base in subject areas where information gaps are found to exist.

3) Augment the observational data base using analytical techniques (theoretical and empirical modeling) to quantify the transport and fate of suspended sediments under a variety of conditions.

1.3 APPROACH

The approach to achieving the first objective was to critically examine the results and conclusions presented in the EIS with respect to basic physical processes. This involved examining the reference material cited in the EIS, as well as searching for any other pertinent literature. Calculations resulting in numerical results stated in the EIS were checked. Weaknesses or omissions in the EIS, as well as gaps in the existing knowledge base related to potential physical impacts of geoduck harvesting, were identified. The results of this review are presented in Section 3.0.

It was clear from the outset that very limited observational data had previously been collected regarding the transport and fate of material suspended by the geoduck harvesting operation. Therefore, it was felt that achieving the second objective of the study would require a limited-scale field measurement program designed to track and quantify the suspended sediment in the plume associated with an actual harvesting operation. A water sampling program was designed and carried out using seven divers at specified fixed sampling stations down-current from an actual geoduck harvest diver working on the Nisqually Reach tract. Results from this experiment were used to extend the existing data base on plume behavior and suspended sediment concentration in the plume, as well as to calibrate the particle tracking model described below. The field data collection program is discussed in Section 4.0.

The third study objective, being the augmentation of observational data with analytical calculations of suspended sediment behavior under a variety of conditions, consisted of three principal elements. In the first element, the transport and fate of the initial plume raised by the harvesting operation was numerically modeled using a particle tracking model. This model jointly considered the physical transport processes of advection (direct transport by currents), settling (particle fall rates as a function of size and density), and dispersion (horizontal spreading and dilution of the plume). The model also allowed consideration of a moving source (the geoduck harvest diver), and incorporated flexibility in the input parameters to facilitate examination of a wide variety of possible application scenarios. The particle tracking model and it's application are described in Section 5.0.

The second element of the analytical approach involved semi-empirical calculations of bottom sediment resuspension under current and wave forces. These calculations were used to evaluate the likelihood of resuspension and further transport of fine particulate material deposited on the bottom after settling out of the initial plume. The results of these calculations are presented in Section 6.0.

The third and final element of the analytical portion of this study involved calculations of beach deposition and erosion parameters in order to assess the likelihood of fine material being deposited in and subsequently eroded from intertidal beach zones near the geoduck harvesting tracts. Section 7.0 describes this analytical approach and results.

We have adopted a conservative scientific approach in all elements of this study. That is, where uncertainty exists, we have made assumptions and chosen techniques that are most likely to err on the side of greater, rather than lesser, impacts on the environment than actually exist. This approach provides a margin of safety in such assessments.

2.0 REVIEW OF EXISTING INFORMATION

The limited amount of time allotted for this study necessitated a focused approach to the examination of existing information. Fortunately, a number of key references were provided or suggested by L. Goodwin (Washington Department of Fisheries) and R. Sternberg (University of Washington) on the subjects of the physical effects of geoduck harvesting and sediment transport, respectively.

2.1 PHYSICAL EFFECTS OF GEODUCK HARVESTING

Very little published information is available on the transport and fate of sediment that is disturbed and/or placed into suspension during the harvesting of geoducks using the hand-held water jet technique. In fact, the only references that could be located presenting any quantitative estimates of the effect of geoduck harvesting on substrate composition were those conducted by Goodwin (1978) and Breen and Shields (1983), both of which were referenced and discussed in the EIS. Goodwin noted changes in sediment grain size distribution between sediments in harvest holes immediately after harvest and in undisturbed nearby substrate that suggested a small but statistically significant loss of fine material (less than 63 micron grain size) from the holes. Breen and Shields concluded that there was no impact on the substrate composition due to harvesting, although their comparisons did not include sediment grain size distribution in holes immediately after harvest.

Studies of suspended sediment and bottom substrate impacts due to commercial hydraulic clam harvesting have been conducted at several locations in Puget Sound (Port Susan, Kilisut Harbor, and Agate Passage) (Schwartz and Terich, 1977; Tarr, 1977), and in the Harraseeket River, Maine (Kyte et al., 1975). The results of these studies indicate that bottom sediment composition, as determined by core samples, was not significantly affected by the clam harvesting operations.

Total suspended solids (TSS) and turbidity in the vicinity of hydraulic clam harvesting operations were found to increase near the bottom at distances of from 50 to 150 yards down-current from the harvest vessel in Puget Sound (Tarr, 1977). However, such effects were found to dissipate quickly, and the incremental elevation in TSS concentrations were small in comparison to the natural variability in suspended material from fluvial sources.

It should be noted that the hydraulic clam harvesting operation is considerably more invasive than the geoduck harvesting technique employing divers with water jets, in that much more sediment is disturbed over a greater area per unit time. Even if the aforementioned studies had determined that significant bottom sediment and water quality impacts existed due to hydraulic clam harvesting, the results would not be directly applicable to geoduck harvesting, due to the different spatial and temporal scales involved.

2.2 SEDIMENT PLUME TRANSPORT

Sediment plumes associated with a number of natural and anthropogenic sources have been studied. Such studies span a range of scales, from major river effluent plumes (tens to hundreds of km) (Barnes et al., 1972) to plumes associated with dredge spoil dumping (tens to hundreds of m) (Nittrouer and Sternberg, 1975). The theoretical basis for sediment transport mechanisms is treated in Graf (1971). Engineering aspects of sediment transport in the nearshore environment are discussed in (USACOE, 1984).

Numerical modeling of plumes has been performed for a variety of applications, including coastal sedimentation and erosion studies, environmental impact assessment for coastal engineering projects, effluent discharge permits and hazardous waste remediation studies, and oil spill trajectory analyses. Unfortunately, the sediment plume induced by geoduck harvesting presents several unique modeling problems, which precluded the use of any "off-the-shelf" models developed for other types of applications. First, the time and spatial scales of the plume are quite small. Second, the source point of the plume (the geoduck diver) is moving in space, unsteady in time (i.e., produces "pulses"), and exhibits a considerable degree of randomness. Third, the plume is ejected into a fluid that has a non-steady-state velocity (i.e., changes in direction and speed with the tide). Finally, from previous studies there is only limited data on the actual source strength (how much sediment is suspended per each hole dug) and no data at all on down-current suspended sediment concentrations for use in model validation. To our knowledge, no previous studies have been performed that address these unique concerns.

2.3 SEDIMENT DEPOSITION AND EROSION

A profusion of reference material exists on the subject of sediment deposition and erosion under the influence of waves and currents in a wide variety of environment types. Much of this material is summarized in review volumes edited by Seymour (1989), Stanley and Swift (1976), and Swift et al. (1972).

In reviewing appropriate techniques for calculating the potential for resuspension of fine sediments deposited from geoduck plumes, as well as possible deposition and erosion of fine material in the intertidal zone, we concentrated on semi-empirical studies (i.e., those using actual field or laboratory measurements, but having an underlying theoretical basis). Examples of such references include: Miller et al. (1977); Komar and Miller (1973, 1975); Grant and Madsen (1979); Southard et al. (1971); and Lavelle et al. (1984). Techniques extracted from these studies formed the basis of the calculations presented in Sections 6.0 and 7.0 of this report. Given the limitations on available data in this study, such semi-empirical techniques were felt to provide the most straightforward and least error-prone means of estimating depositional/erosional tendencies.

3.0 TECHNICAL REVIEW OF THE EIS

Our review was limited to an evaluation of the EIS with regard to the physical aspects of the natural environment. Consequently, we focused on Subsections 3.1 (Earth), 3.2 (Air), and 3.3 (Water), within Section 3.0 (ASSESSMENT OF IMPACTS TO THE NATURAL ENVIRONMENT). Each of these subsections are discussed below. First, however, we offer several general comments on the content of the EIS.

The authors of the EIS were hampered by the lack of observational or model output data upon which to base their conclusions. Given this limitation, the subject sections provide a reasonable attempt to quantify some of the more obvious effects that might be associated with sediment suspension during harvesting activities. These include rough calculations of the thickness of redeposited plume material and changes in the suspended sediment concentration in the overlying water. Our overall finding is that the general conclusions in the EIS regarding impacts to the physical environment due to commercial geoduck harvesting are valid. We did, however, identify some deficiencies in the EIS discussions in the form of subject matter omissions and numerical inconsistencies.

First, there was no quantitative discussion of the transport and fate of the initial plume produced by the harvesting activity. As the EIS states, no studies had been conducted to actually follow the displaced material. This emphasizes the speculative nature of many of the numerical results presented.

There was also no attempt to quantify the likelihood of resuspension and further transport by waves and currents of unconsolidated sediment redeposited on the bottom after settling out of the plume. Some readily available references or relatively simple calculations could have provided a rough determination of the possible importance of such processes. Likewise, there was no discussion of the possible deposition and likelihood of retention of fine suspended sediments in the intertidal zone of beaches surrounding the harvest tract.

Finally, there was no discussion of bottom sediment placed into suspension by the activities of the geoduck divers, beyond that disturbed during the digging of the actual hole. Through conversations with Washington Department of Fisheries (WDF) and Department of Natural Resources (DNR) personnel, and first-hand observation of a harvest diver in action, it became apparent to us that a significant amount of surficial sediment is disturbed by the diver's activities, including moving (or "jetting" with the water jet) along the bottom and dragging hoses or bags. Although estimation of the quantity of sediment disturbed in this manner is virtually impossible, visual appearances suggest that it may amount to a significant additional source of suspended material beyond that which is displaced in the actual digging of the holes. Furthermore, the diver's activities not only raise more suspended sediment, but his movement around or through the initial plume also serves to disperse the suspended material over greater horizontal and vertical scales than would be expected due to natural advection and dispersion processes in the current. Consequently, impact estimates based only on the loss of material from the actual holes are likely to be underestimates.

3.1 EARTH

Section 3.1 of the EIS (p. 107-110) discusses potential impacts due to geoduck harvesting on the bottom sediment distribution and composition. The numerical estimates given in this section are based entirely on data presented by Goodwin (1978), which is appropriate given that Goodwin's study was the only known source of data (prior to the present study) specifically dealing with bottom sediment changes immediately after geoduck harvesting. We confirmed that the calculated results presented in this section were correct in light of Goodwin's data. One of the findings states that if all the fine material released from the geoduck holes in a given tract during a year's harvest were redeposited on the tract itself (a conservative assumption), it would constitute a layer only 0.02 cm thick. That such a small layer is inconsequential could have been underscored if it had been compared to estimates of annual average natural sedimentation in various areas of Puget Sound. For example, the natural sedimentation rate in the Nisqually delta area is approximately 1.7 cm/yr (Brundage, 1960), two orders of magnitude greater than the conservative EIS estimate.

The main weaknesses of this section of the EIS include: lack of discussion of sediment suspended by the diver's activities; lack of estimates of potential resuspension of unconsolidated bottom sediment by wave and current forces; and lack of discussion of potential intertidal zone deposition and retention of fine sediments. The point should also have been made that Goodwin's results, upon which the numerical estimates in this section were based, came from an experimental (not commercial) plot in Hood Canal, and may not be directly transferable to other Puget Sound sites due to differences in substrate composition.

Although the above topics should have been addressed, we believe that their consideration would not have changed the overall conclusions in the EIS regarding the significance of substrate impacts.

3.2 AIR

After consideration of the small number and spatial separation of the boats involved in harvesting, we concur with the conclusion that there will be no significant impact on air quality.

3.3 WATER

Some omissions and inconsistencies were noted in reviewing the numerical results presented in this section of the EIS.

In paragraph 1, page 112 ("No studies have..."), physical dimensions of the suspended sediment plume down-current from the harvesters are provided. This is a critical issue, yet no reference is provided on the source of this information.

Paragraph 2, page 112 ("Goodwin (1978c) observed...") presents several numerical results in inconsistent units (liters, cubic meters, gallons). There also appears to be a numerical error in this paragraph, where it is stated that "the amount of fines released from an average harvest hole is equivalent to about 0.91 liters...". This number is inconsistent with both the calculations presented on page 109 and the estimate of 0.81 cubic meters of fines released in 10,000 holes presented later in this paragraph. There appears to be an approximate factor of ten error in the 0.91 liter value. However, this number does not appear to have been used in subsequent calculations described later in this paragraph. The estimated change in suspended solid concentration of 0.2 ppm by volume is correct.

4.0 FIELD DATA COLLECTION

4.1 OBJECTIVES

Given the very limited amount of existing data on the transport and fate of sediment suspended during geoduck harvesting, the objectives of the field data collection portion of this study were:

(1) To provide additional observational data on the behavior of the suspended sediment plume associated with commercial geoduck harvesting; and

(2) To provide actual in-situ measurements that could be used to calibrate the numerical model used in this study.

4.2 METHODS

The field data collection activity, which occurred on February 18, 1992, was coordinated by Pentec Environmental. WDF, DNR and Ebasco Environmental staff participated in the experimental design and assisted with field logistics. Prior to finalizing the sampling design, Ebasco Environmental and Pentec staff participated in an orientation dive in the company of DNR divers to observe an actual commercial harvesting operation and the resulting plume.

The importance of obtaining realistic measurements dictated that the field experiment occur during an actual commercial harvesting operation in an existing commercial tract. To this end, cooperation with commercial harvesting operators was sought and obtained. The experiment occurred in the western portion of the Nisqually Reach Tract near Sandy Point.

Two types of sediment data were required. These included total suspended solid (TSS) concentrations in the affected water column down-current from the harvester, and particle size distributionss from bottom sediment cores collected in the immediate vicinity of the experiment.

4.2.1 TSS

A sampling plan was devised to allow a series of synoptic "snapshots" of TSS concentration at seven locations ranging between zero and 100 m down-current from the geoduck harvesting operation (Figure 4-1). A sampling grid was laid out on the bottom using measured lines, and sampling locations were marked by floats attached to small anchors. The long axis of the sampling grid was chosen to align with the prevailing flood tidal current at the experimental site (as determined by diver observation of near-bottom drift direction).

A 30 m by 30 m square in which the geoduck diver was to work was also marked by lines on the bottom. Timing was coordinated between the geoduck diver and seven sampling divers stationed near the bottom at the designated points on the sampling grid. The geoduck diver actively harvested geoducks within the square from time=0 to time=20 minutes, while the sampling divers collected 1-liter water bottle samples every five minutes, starting at time=0 and ending at time=30 minutes (ten minutes after the geoduck diver stopped harvesting). Before and after his harvesting activity, the geoduck diver remained stationary, and water pressure to his hand-held jet was turned off to avoid unintentional sediment disturbance. Upon conclusion of the experiment, the geoducks harvested by the diver were counted. During the 20 minute harvesting period, the diver harvested 24 geoducks, yielding an average time interval of 50 seconds between holes.

All of the sampling divers were instructed to collect samples at approximately 1 m off the bottom. The divers stationed at the two farthest down-current stations (60 m and 100 m) collected double samples to allow more accurate determination of low concentration values.

The water bottle samples collected during the experiment were submitted within 24 hours to an analytical laboratory for analysis of TSS and turbidity.

4.2.2 Bottom Sediment Composition

In addition to the water samples, three bottom sediment cores were collected on the day of the experiment by a diver using a hand-held coring device. These included two control cores taken in undisturbed sediment adjacent to the experiment grid, and one core taken in a harvested geoduck hole shortly after harvest.

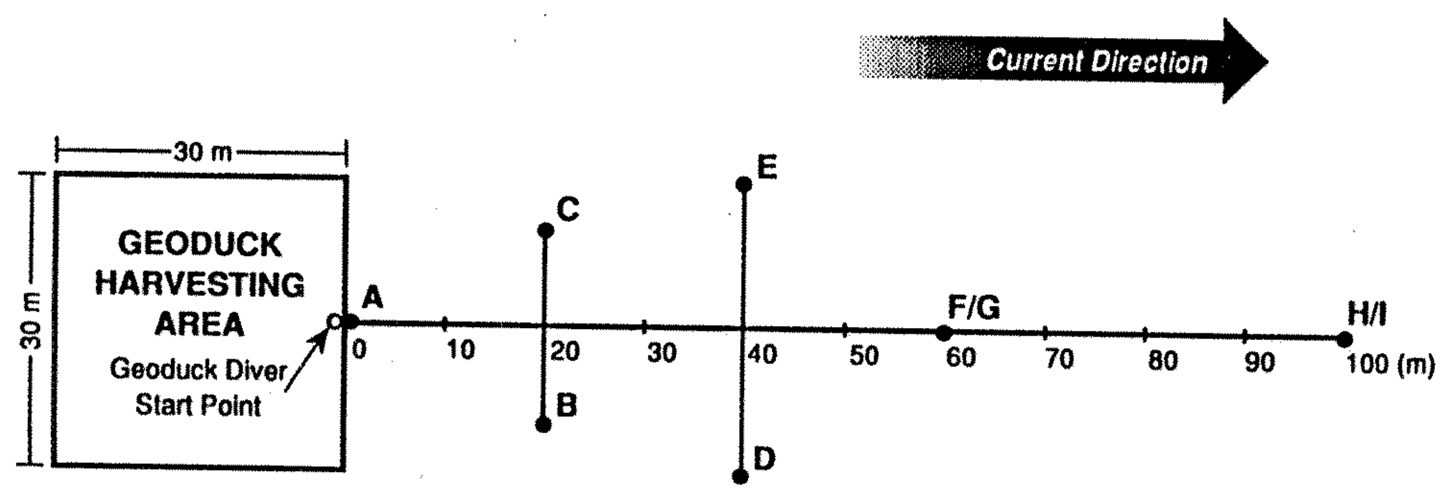


Figure 4-1. Field sampling station locations.

The three core samples were refrigerated and submitted within 24 hours to an analytical laboratory for grain size analysis.

4.2.3 Current Speed

The timing of the experiment was set to coincide with the maximum predicted flood current of the day. Although the predicted maximum flood current was approximately 0.5 m/s (1 kt) for the central Nisqually Reach (NOAA Tidal Current Tables), we anticipated a lower current in the experiment area further west.

During the course of the experiment, current measurements were taken from a support boat immediately adjacent to the experiment grid. The current meter used was a Swoffer Model 2100, with an on-deck digital readout in m/s. The averaging period was set at 30 seconds. This instrument has a nominal speed measurement threshold of 0.03 m/s.

Seven current measurements were manually recorded during the 30 minute experiment. The measurement height above the bottom alternated between 1 m and 3 m, in order to encompass the likely vertical extent of the plume.

4.3 RESULTS

4.3.1 TSS

The TSS results are summarized in Table 4-1. In general, TSS during the experiment was very low. The background value, as determined from samples taken at time t=0 and at stations too far down-current to be affected by harvesting-related plumes, averaged approximately 4 mg/l, which is the minimum reporting limit used by the laboratory in analysis of TSS. In several cases, the value measured was below the reporting limit. For these samples, we assumed a TSS value equal to the average background. Table 4-1 also presents the calculated deviation from background, determined by subtraction. This deviation from background was used in comparing the observed results to the modeled results (see Section 5.3).

The double water samples collected by the divers farthest down-current (60 and 100 m) were combined in the analysis. For unknown reasons, TSS values from one station (H/I) appeared to be contaminated for several sampling times, as indicated by inconsistency

Table 4-1. Total suspended solid (TSS) concentrations measured at plume sampling stations at the Nisqually Reach experiment site, February 18, 1992.

Time (min)	TSS (mg/l)							TSS Deviation From Background (mg/l)[1]						
	A[2]	B	C	D	E	F/G	H/I	A	B	C	D	E	F/G	H/I
0	13	5	4	<4[3]	<4	5	10[4]	9	1	0	0	0	1	6[4]
5	7	5	<4	<4	5	<4	9[4]	3	1	0	0	1	0	5[4]
10	21	4	4	4	5	5	6[4]	17	0	0	0	1	1	2[4]
15	4	5	<4	6	4	5	<4	0	1	0	2	0	1	0
20	10	9	10	4	5	<4	<4	6	5	6	0	1	0	0
25	14	<4	4	4	5	5	12[4]	10	0	0	0	1	1	8[4]
30	13	<4	4	4	8	11	4	9	0	0	0	4	7	0

1/ Background was determined to be 4 mg/l.
2/ See Figure 4-1 for station locations.
3/ Values given as "<4" indicate a concentration below laboratory reporting limit. Deviation from background in such cases was set at zero.
4/ Sample suspected of possible contamination.

with the other samples and the probable timing of plume movement given the measured current.

As expected, the highest TSS values were reported at station A, closest to the harvest diver. Increases in TSS were also seen at stations B and C at t=20 minutes, and at stations E and F/G at the end of the experiment (t=30 minutes). Since uncertainty exists regarding the data validity at station H/I, we can only say with some confidence that the plume generated by the geoduck diver reached station F/G, 60 m down-current, by the end of the experiment. This is roughly consistent with the measured current speed during the experiment, which averaged 0.034 m/s (see Section 4.3.3 below). At this average speed, the plume front would have been advected 61.2 m from the source during 30 minutes.

4.3.2 Bottom Sediment Composition

The grain size analysis for the three bottom sediment cores is shown in Table 4-2. Grain size percentages were determined for three size categories: greater than 500 microns (coarse sand), 62.5 to 500 microns (fine and medium sand), and less than 62.5 microns (silt and clay). The last category is most relevant to this study, since the fine sediments ("fines") are those which remain suspended longer, and are available for transport and redeposition away from their source substrate.

The three cores taken at the experiment site are very similar in grain size composition. The core taken in the geoduck harvest hole soon after digging shows slight reductions in both coarse and fine fractions, in apparent agreement with the findings of Goodwin (1978). However, with only three samples, the small differences in the results shown here cannot be considered significant. Goodwin (personal communication) has indicated that typical values of fine sediment percentage for geoduck beds range from about 4 to 10 percent. The average value of 8 percent determined from the three cores collected in this experiment are therefore within the normal range. The 8 percent value was used in the numerical modeling portion of this study.

4.3.3 Current Speed

Measured current speeds during the experiment were weak and variable, in many cases at or below the nominal measurement threshold of the current meter (Section 4.2.3). The

Table 4-2. Sediment core grain size composition (percent by weight in each size class) for three bottom cores taken at the Nisqually Reach experiment site, February 18, 1992.

Sample	Grain Size (microns) >500	62.5-500	<62.5
Control A[1/]	5	86	9
Control B[1/]	5	87	8
Hole[2/]	4	88	7

1/ Control samples were taken in undisturbed substrate immediately adjacent to the experiment site.

2/ Hole sample was taken in a recently harvested geoduck hole within the experiment site.

absolute accuracy of the measurements is therefore uncertain. However, the average speed of the measured current (Table 4-3) was found to be consistent with the apparent movement of the suspended sediment plume, as indicated by the TSS samples.

Table 4-3. Current speeds measured at the Nisqually Reach experiment site, February 18, 1992.

Time[1/] (min)	Current Speed (m/s)	Height Above Bottom (m)
-2	0.04	1
0	0.06	1
6	0.01	3
10	0.00	1
15	0.02	3
16	0.09	3
20	0.02	1
	Average 0.034	

1/ Time referenced to start of TSS sampling.

5.0 TRANSPORT AND FATE OF INITIAL PLUME

5.1 MODEL DEVELOPMENT

5.1.1 Approach

There are three general types of models that might be used to simulate the transport and fate of particulate matter placed into suspension during geoduck harvesting:

1. Particle tracking models, in which the transport and settling of individual particles are simulated.

2. Analytic models that simplify the governing transport and fate equations to a point where a simple expression is developed. Generally, simplifying assumptions include steady-state currents.

3. Numerical models that directly solve the governing transport and fate equations.

In general, we preferred the first approach due to its efficiency and relative conceptual simplicity. In our view, analytic models are too limiting, and numerical models, while providing a complete description, are not as straightforward as particle tracking models for this application.

The modeling tasks in this study faced several unique complicating factors which precluded the use of existing models developed for other sediment transport applications. Principal among these complications were the facts that the suspended sediment source (the geoduck harvester) is moving spatially, unsteady in time (i.e., generates pulses), and injects material into a fluid having a periodic current variation (tidal current). Furthermore, considerable uncertainty existed regarding the source strength (amount of material suspended per unit time).

5.1.2 Processes Simulated

The particle tracking model, GEODUCK, simulates the following processes:

1. Source distribution of particles
2. Moving source
3. Particle advection
4. Three-dimensional dispersion
5. Particle settling

<u>Source Distribution of Particles</u>

We assumed that each hole created during geoduck harvesting produces a known quantity of particulate material. For the purposes of defining this quantity, we have used average hole size estimates given by Goodwin (1978). Given a possible range of sediment saturation, the resulting variation in density implies that approximately 20 kg of material is displaced in each hole.

It is also necessary to know the distribution of particle grain sizes in the displaced material. For the Nisqually Reach tract, the grain size distribution was obtained from sediment cores taken by Pentec Environmental as part of the field data collection program (see Section 4.0). This grain size distribution is within typical ranges found by Goodwin (personal communication) for geoduck beds. For adequate model simulations in other areas, site-specific bottom sediment composition data would be required.

Using the number of sediment size classes provided in the bottom core data, GEODUCK subdivides each size class into an equal number of intervals based on the user-specified number of particles for that class. The weight of each particle is determined by the diameter of the particle, and scaled by the percentage range of the size class and the number of particles released. Finally, the individual particle weights are scaled to the total weight of particulates released from a hole.

Each hole created is assumed to release material into a cylindrical volume of user-specified dimensions. All of the particles simulated for each hole are released randomly into this initial cylindrical volume. Based upon first-hand observations, and discussion with WDF and DNR personnel, we set the cylinder's height at 1.5 m and diameter at 2.0 m for all model runs. This initial dilution volume was intentionally chosen to be somewhat larger than the initial plume raised by digging the geoduck, in the hopes of partially accounting for the dispersive activities of the diver himself.

Moving Source

If the down-current area of concern is relatively far from the harvesting site, the movement of the source (the diver) may not be very important in determining suspended sediment concentrations. However, in the most conservative approach, the source movement must be taken into account in assessing near-field maximum suspended and settled out concentrations.

In GEODUCK, a moving source is permitted along a user-specified track. The track of a diver is defined by as many x-y positions and times as may be applicable. The user specifies the time increment between geoduck holes, and the model then interpolates hole positions as a function of time along the specified track. In our model simulations, we used an idealized "zig-zag" path for the diver moving generally up-current, and assumed a time increment of 50 seconds between each hole, in line with field observations.

Particle Advection

Advection represents the direct transport of particles by the current. Ambient currents are assumed to be of a sinusoidally varying form, with an amplitude equal to the maximum tidal current at any location, and a period equal to the tidal period (12.42 hours). The coordinate system used by the GEODUCK model is aligned with the major current direction, so that the particle displacement due to advection between any two time steps is simply given by the current speed multiplied by the time step.

Particle Dispersion

Dispersion is the three-dimensional spreading process in a fluid due to random turbulence within the velocity field. This model allows the user to specify the lateral, longitudinal, and vertical dispersion coefficients, based on previous empirical studies or model calibration runs. We chose horizontal dispersion coefficients that were a factor of ten (order of magnitude) larger than the vertical dispersion coefficient, based on visual field observations that indicated only small vertical dispersion of the suspended sediment plume.

The dispersion calculation used in GEODUCK introduces randomness into the motion of each particle. Consequently, it is not possible to exactly duplicate the results of a given model run. However, when a large number of particles are simulated, the statistics of the three-dimensional mass distribution are preserved.

Particle Settling

The particle settling algorithm in GEODUCK follows the approach described in USACOE (1984). In this method, a buoyancy parameter is defined, that is a function of the specific gravities of the fluid and the particles, the kinematic viscosity of the fluid, and the particle diameter. The functional relationship between these variables produces settling velocities that are in close agreement with classical semi-empirical formulations (Sverdrup et al., 1942).

Our approach did not take into account possible flocculation (aggregation) of very fine particles. Although this phenomenon is known to occur for fine silt- and clay-sized particles (less than about 10 microns in diameter), it is very difficult to quantify (R. Sternberg, personal communication). Disregarding this process, however, may be seen as a conservative assumption, since any flocculation occurring will tend to increase the size and weight of the particles, and cause more rapid settling of fine suspended material.

5.1.3 Model Input and Output

The GEODUCK model was designed to allow the user a great deal of flexibility in specifying input parameters so that the model can be used in a wide variety of different situations. Model input variables that may be specified by the user include:

- Mass of sediment released per hole
- Sediment grain size distribution
- Specific gravity of the sediment
- Number of particles to be simulated in each size class
- Dimensions of initial dilution volume
- Time interval between geoduck holes

- Diver track
- Maximum current speed
- Water depth
- Dispersion coefficients
- Harvesting duration and model simulation duration
- Dimensions of the simulation area

The model produces two types of two-dimensional mapped display output:

- Spatial distribution of TSS concentration in g/m^3 (equivalent to mg/l)
- Spatial distribution of settled mass concentration in g/m^2

Note that the TSS concentrations computed are in reality deviations from background, since the model is simulating only effects from the geoduck harvesting source. To obtain the true TSS, it would be necessary to add in the background concentration, if known.

5.2 MODEL TESTING

The program GEODUCK was subjected to a number of basic performance tests to ensure that it was operating properly. The simulations were designed to test each component of the program.

The first test was to ensure that the program was correctly advecting particles. The model was modified to use a constant velocity, and the particle positions printed out after a specified time interval. Results were found to agree with constant advection calculations.

The second test was to ensure that particle settling was correctly programmed. For this test, the particle diameters, positions, and computed settling velocities were printed out. Examination of the results confirmed that the model was operating properly.

The third test was of model dispersion in one dimension (the longitudinal direction of flow). For an instantaneous disturbance of mass, the concentration of particulate mass at the center of the plume was compared to theoretical results for two time periods. The results were in close agreement.

The fourth and final basic performance test was to examine the source terms. A track was defined and the coordinates of the individual holes printed out to ensure that the model was correctly simulating their locations. In addition, at the end of each simulation, a mass balance table was printed out that accounted for the mass settled, the mass in suspension, and the mass that had left the specified grid area. In all cases, the holes were correctly located, and the total amount of particulate mass was conserved.

In addition to the model performance tests, an additional series of test simulations were run to test the sensitivity of the model to changes in various input parameters. Sensitivity tests were run to examine the effects of changing the source strength, dispersion parameters, particle grain size distribution, diver track, and current speed. By means of these tests, we were able to arrive at tentative values of input parameters that appeared to produce the most realistic simulation of visually observed plume behavior.

5.3 MODEL CALIBRATION

The tests described in the previous section brought the model to a point where we were confident it was working properly. The next step involved using actual field data to calibrate the model. In the calibration process, model parameters are adjusted to achieve maximum agreement between observed and modeled results. This then allows further modeling to examine scenarios for which no observed data exist.

The field data used for model calibration consisted of TSS values determined for the nine sets of water samples collected by divers down-current from a geoduck harvester during the field study described in Section 4.0. The model calibration results showing best agreement with observations produced an average error of (-) 0.4 mg/l, a root-mean-square (RMS) error of 3.0 mg/l, and a correlation coefficient of 0.7 (significant at the 99% confidence level for n=39). Some sample data collected by the farthest downcurrent diver (H/I) appeared to be contaminated, and were excluded from this analysis (see Section 4.3).

Based upon these results, we concluded that the source terms, dispersion coefficients, settling rates, and other model variables were set at reasonable values, and the running of further simulation scenarios could proceed.

5.4 MODEL APPLICATION

5.4.1 Description of Modeled Scenarios

For the purposes of this study, all of the input variables were set at reasonable values based on the calibration calculations and held constant, with the exception of the current speed. Four separate model simulations were run, using the following current speeds: 0.05 m/s, 0.25 m/s, 0.5 m/s, and 1.0 m/s. These current speeds were chosen to cover the range of current speeds that would be typically encountered on commercial geoduck harvest tracts.

The model grid was set up using the same 30 m x 30 m harvesting area defined in the field experiment, and an idealized zig-zag path was specified for the geoduck diver. As in the case of the field experiment, for each model run the diver was assumed to harvest for a total of 20 minutes, digging a hole every 50 seconds (averaging 1.2 holes per minute).

The down-current length of the model grid was set at 200 m. This distance was chosen because it corresponds approximately to the 200 yd offshore limit to which the commercial harvesters are restricted. Under hypothetical conditions in which the current would be oriented directly onshore, this configuration would represent the worst case for transport of suspended sediment into the intertidal zone. Of course, a directly onshore current is a highly unrealistic scenario, since nearshore currents tend to be predominantly alongshore. However, the onshore transport assumption does provide the most conservative estimate of impacts in the intertidal zone.

The total size of the model domain used in these runs was set slightly larger than the harvesting area and down-current grid, to ensure that horizontal dispersion did not carry material out of the model domain in the up-current or lateral directions. The total dimensions of the model domain were 60 m x 240 m, for a total area of 14,400 m^2.

5.4.2 Model Results

Figures 5-1 through 5-4 show the model results for TSS for the four current speeds specified. Each of these figures presents concentration values at the end of the 20 minute harvesting period, which represents the time in each model run at which the maximum amount of sediment is suspended in the water. The concentrations (in mg/l) have been contoured at logarithmic intervals (powers of ten).

These plots show that the highest concentrations (greater than 100 mg/l) are confined to a small area surrounding the last hole dug by the diver. Also, the results aptly illustrate how the plume loses its integrity as the current speed increases. At the higher current speeds (0.50 m/s and 1.0 m/s), the suspended sediment down-current from the source is segregated into self-contained clouds of suspended sediment, each representing the material released during the digging of one hole.

The concentration of material settled on the bottom for each of the four current speed cases is depicted in Figures 5-5 through 5-8. For these model runs, the simulation time was extended long enough so that no material remained suspended in the water within the model domain; that is, all of the sediment in the plume either settled out or was advected out of the model domain (past the 200 m line). For these simulations, then, the contours shown (in logarithmic intervals) represent the maximum bottom deposition. Units of settled concentration are g/m^2.

These plots show that at low current speeds, the pattern of deposition closely followed the diver's track, and the highest settled concentrations were found almost entirely inside the harvesting area, within a few meters of the harvested holes. As the current speed increased, the pattern of deposition was displaced down-current and showed less resemblance to the diver's track. For the 0.05 m/s case, virtually all deposition occurred within the first 100 m down-current from the harvesting area. For the three higher current speed cases, small quantities of material were deposited all the way to the 200 m endpoint.

Although the model does not compute a settled sediment thickness, such a conversion is relatively simple if one assumes a representative sediment bulk density. The sediment bulk density takes into account the density of the solid grains themselves (assumed to be 2.65 g/cm^3), as well as the porosity of the settled sediment and the density of the

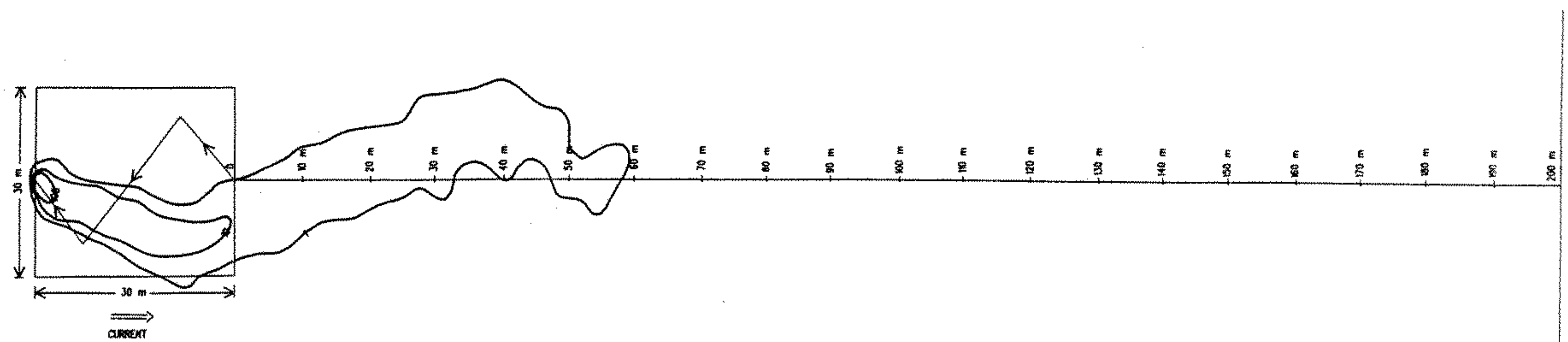


Figure 5-1. TSS contours (mg/l).
Time = 20 minutes.
Current speed = 0.05 m/s.

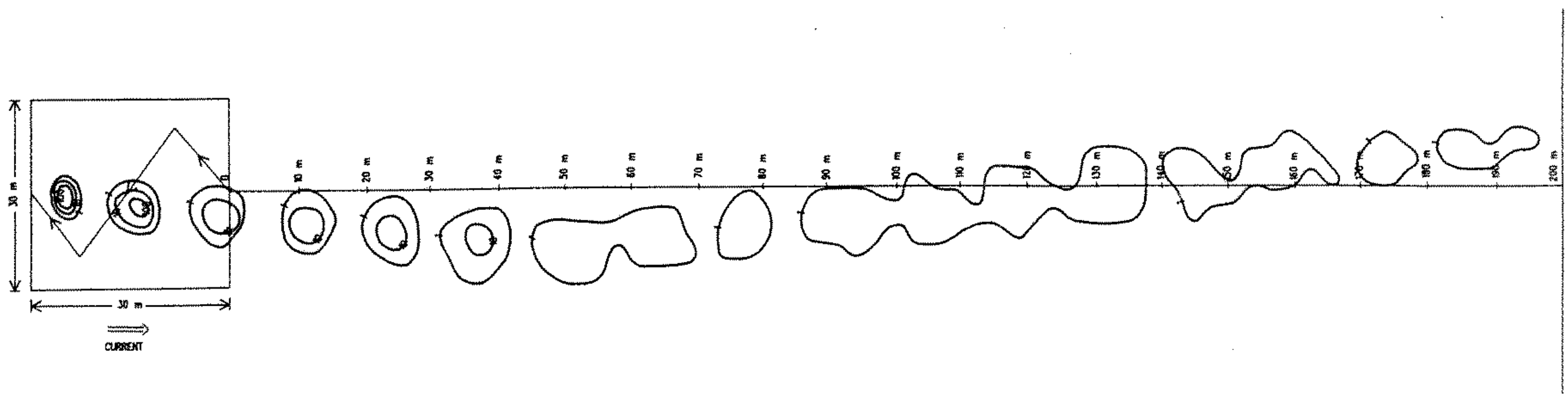


Figure 5-2. TSS contours (mg/l).
Time = 20 minutes.
Current speed = 0.25 m/s.

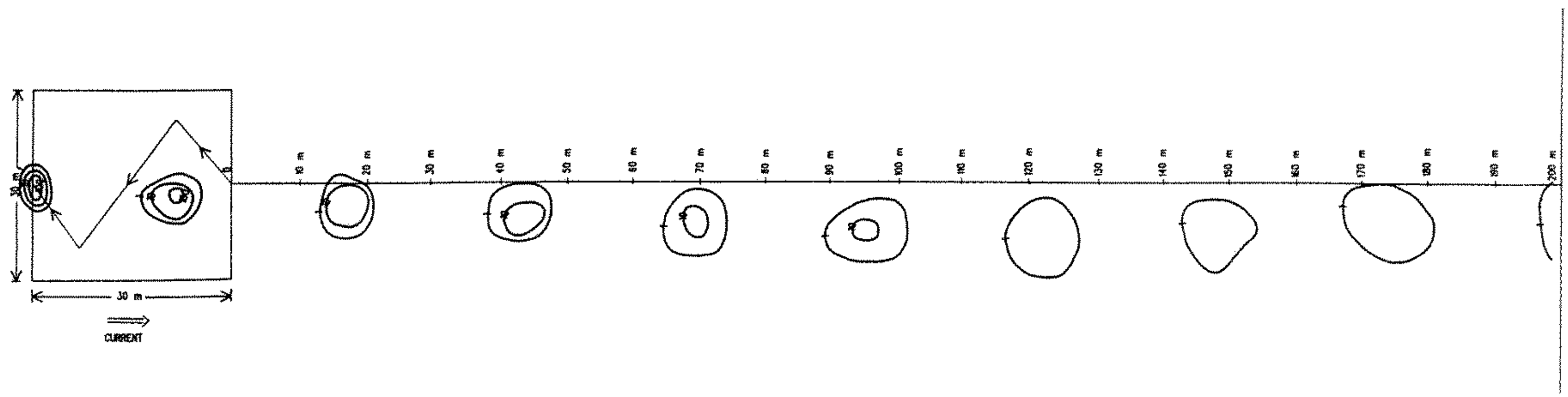


Figure 5-3. TSS contours (mg/l).
Time = 20 minutes.
Current speed = 0.5 m/s.

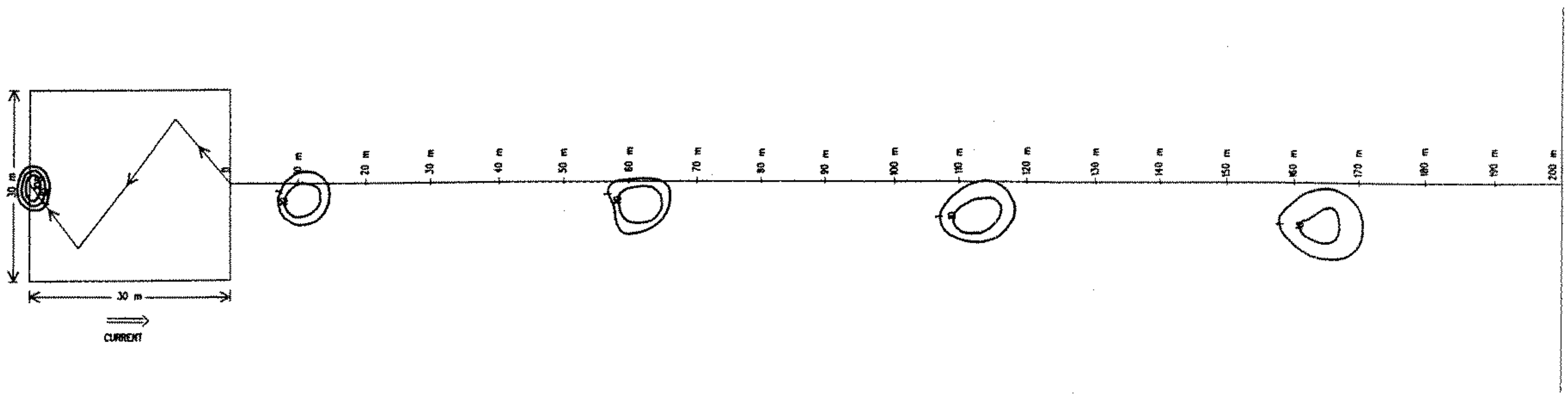


Figure 5-4. TSS contours (mg/l).
Time = 20 minutes.
Current speed = 1.0 m/s.

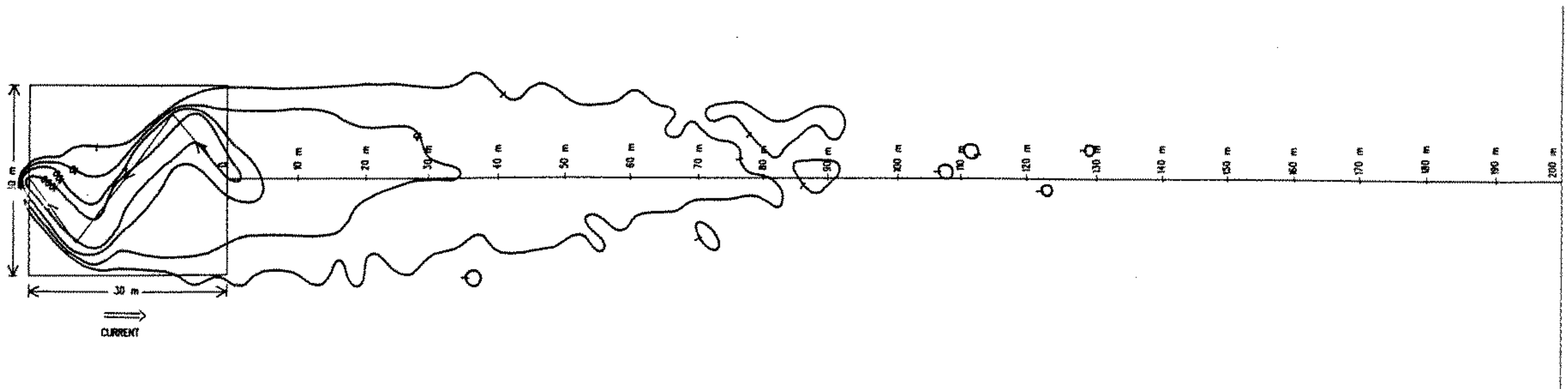


Figure 5-5. Settled concentration contours (g/sq. m).
Time = 120 minutes.
Current speed = 0.05 m/s.

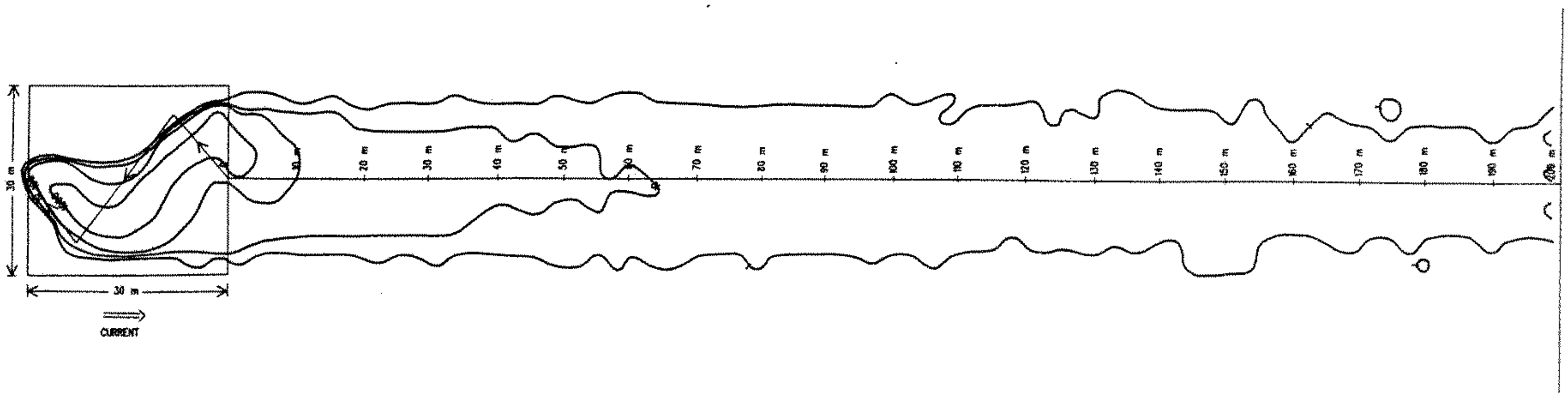


Figure 5-6. Settled concentration contours (g/sq. m).
Time = 45 minutes.
Current speed = 0.25 m/s.

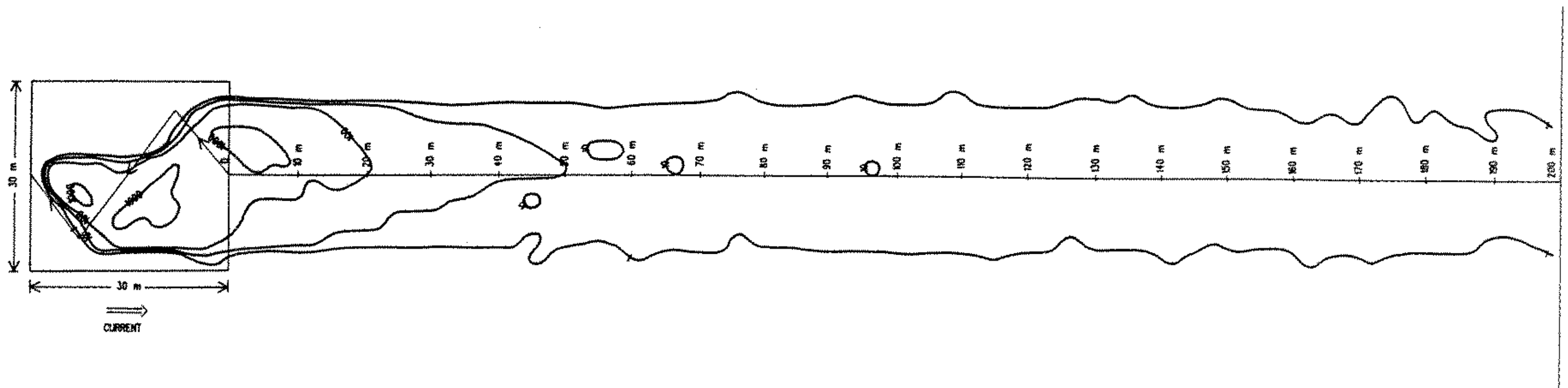


Figure 5-7. Settled concentration contours (g/sq. m).
Time = 30 minutes.
Current speed = 0.5 m/s.

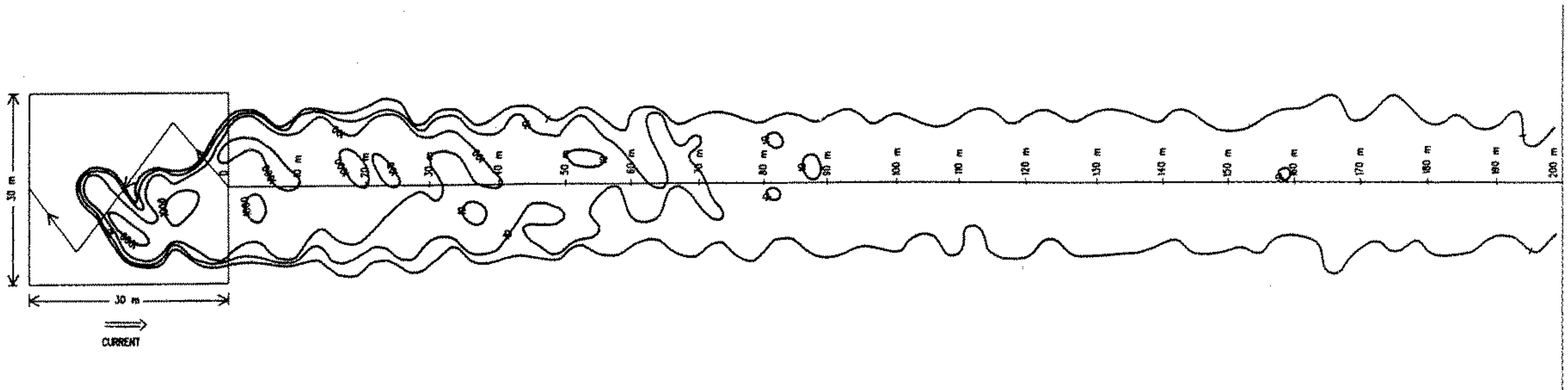


Figure 5-8. Settled concentration contours (g/sq. m).
Time = 30 minutes.
Current speed = 1.0 m/s.

seawater in the pore spaces. Using a porosity value of 0.5, which is typical of a combination of fine sand and fine sandy silty clay (Dyer, 1986), calculations yield a sediment bulk density of 1.84 g/cm^3 (R. Sternberg, personal communication). The conversion from settled concentration in g/m^2 to settled thickness in centimeters may then be carried out by simply dividing by 18,400.

The maximum settled concentration found in any of the four current speed scenarios was 3,118 g/m^2 (for 0.05 m/s), at a model output gridpoint located within 1 m of a geoduck hole. Using the above approximate technique, this maximum settled concentration equates to a maximum depositional thickness of only 0.17 cm (1.7 mm). Area average settled concentrations and thicknesses for each current speed were computed by dividing the total mass of sediment settled by the affected area, which is defined as the area encompassing all model output gridpoints exhibiting non-zero values. The results of these calculations are presented in Table 5-1. The area average settled concentrations and thicknesses were extremely small and of the same order of magnitude for each of the four current speeds. Implications of these results with respect to cumulative effects over longer time periods will be discussed in Section 5.4.4.

5.4.3 Shoreline Deposition

As may be seen in Figures 5-1 through 5-8, for the worst case in which the current is pointed directly onshore, some small amount of suspended material would reach the shoreline 200 m from the harvesting area. Using the model results, we calculated the amount of material that would be available for deposition in the intertidal zone per 100 m of shoreline, per hour of geoduck harvesting. In this calculation, we assumed that all of the available material will be deposited in the intertidal zone during a tidal cycle. In order to estimate the area of the intertidal zone, we assumed a beach slope of 1:10 and a tidal range of 4 m. For a shoreline length of 100 m, this yields a total intertidal area of 4020 m^2, slightly less than 1 acre. The results of the deposition calculation are shown in Table 5-2. As the table shows, the resulting thicknesses of material deposited in the intertidal zone per hour of harvesting are extremely small. Implications of these results with respect to cumulative effects over longer time periods will be discussed in the next section.

Table 5-1. Average settled sediment concentration and thickness over the affected area[1/]. Assumes 25 holes dug over a 20 minute duration.

Current Speed (m/s)	Affected Area (m^2)	Total Mass (kg) Settled in Area	Area Average Concentration (g/m^2)	Area Average Thickness (cm)[2/]
0.05	7,047	499.68	70.9	0.0039
0.25	6,660	494.94	74.3	0.0040
0.50	6,246	488.14	78.2	0.0043
1.00	5,427	478.97	88.3	0.0048

1/ Affected area is defined by the area encompassing all model output gridpoints exhibiting non-zero values.

2/ Assumes sediment bulk density of 1.84 g/cm^3.

Table 5-2. Material available for deposition in the intertidal zone per 100 m of shoreline per hour of geoduck harvesting[1/].

Current Speed (m/s)	Mass of Sediment (kg) Per Hour Per 100 m Shoreline Available for Deposition	Area Average Thickness (cm)
0.05	3	0.00004
0.25	46	0.0006
0.50	107	0.001
1.00	189	0.003

1/ Assumes the following: 75 holes dug per hour in a 30 m x 30 m area; harvest tract is 200 m from shore; current is directly onshore; beach slope is 1:10; tidal range is 4 m; all available material is deposited; bulk sediment density = 1.84 g/cm^3.

5.4.4 Cumulative Effects

Cumulative effects on the physical environment due to geoduck harvesting are difficult to quantify using the modeling results described above, because of the small spatial and temporal scales associated with the plumes. A simple and conservative approach, however, is to simply scale the modeling results upward by a factor that would approximate the harvesting intensity over a given area during the course of a year. The EIS states that approximately 10,000 holes per acre are dug annually on an average commercial geoduck bed. The 30 m x 30 m harvesting area we modeled equates to 900 m^2, or roughly 1/4 acre. Therefore, 2,500 holes in that area would approximate the typical hole density over the course of a year. Since 25 holes were dug in each of our simulation runs, scaling the settled concentrations (or thicknesses) by a factor of 100 would provide a worst-case estimate of long-term cumulative effects. Applying this factor to the area average thicknesses given in Table 5-1 yields area average cumulative thicknesses of approximately 0.4 cm. The EIS gives a numerical estimate of 0.02 cm for the thickness of material that would result if all the fine material released from 10,000 holes per acre were to resettle on the tract. The 0.4 cm and 0.02 cm values are not inconsistent, considering that the 0.4 cm thickness incorporates all grain sizes, not just the fines released. In any case, the depositional thickness is extremely small.

The same factor of 100 can be applied to the intertidal zone depositional thicknesses presented in Table 5-2. Again, even with an increase of two orders of magnitude, the worst case depositional thickness in the intertidal zone would be inconsequentially small.

In the above cumulative estimates, it is assumed that all of the material deposited stays in place, and cumulative deposition would be simply additive over time. In reality, this assumption will not be valid during certain times and in certain locations in Puget Sound, due to current and wave forces governing the process of sediment resuspension. These effects are discussed further in Section 6.0.

5.4.5 Applicability of Results to Other Sites in Puget Sound and Hood Canal

In general terms, it can be said that similar physical processes tend to operate in similar physical environments. To the extent that one site resembles another in terms of the physical environment (shoreline morphology, bottom sediment composition, current and wave climates), model results generated for the two sites should be correspondingly similar.

The GEODUCK model was calibrated using field data collected on the Nisqually Reach tract. However, the model was specifically designed to be nonrestrictive in its application; that is, flexibility in user input allows the model to be used in a variety of different environments. The two primary site-specific pieces of information that would be required to apply the model at some other site in Puget Sound are the bottom sediment composition (grain size distribution) and the tidal current speed.

Historical data on bottom sediment composition for many areas in Puget Sound and Hood Canal were summarized by Roberts (1974). Other bottom sediment data have been collected by WDF and other state agencies. These sources may or may not provide actual site-specific data for commercial geoduck harvest tracts. Ideally, sediment composition data collected on an actual harvest tract (or proposed tract) should be used for model input.

Current speeds at locations away from official tidal current prediction points are difficult to estimate. Published tidal current charts may be of some use in this regard. Onsite measurements would of course be preferable. Where uncertainty exists, the model can be used to examine effects associated with a range of current speeds.

6.0 RESUSPENSION OF UNCONSOLIDATED BOTTOM SEDIMENT

The sediment that settles out of the plume will initially be in an unconsolidated form. As time progresses, its water content will decrease, and its shear strength and resistance to erosion will gradually return to the initial state. The time scale over which this reconsolidation will occur is uncertain. However, in laboratory experiments with fine-grained marine sediment, Southard et al. (1971) determined that the resistance to resuspension, as indicated by the threshold erosion velocity, tends to double in time periods on the order of 12 hours. The evidence suggests, therefore, that redeposited material will tend to regain its original shear strength within one or two days, assuming that there is no further disturbance during that time.

During the period in which the sediment remains unconsolidated, it will be subject to resuspension by current and wave forces. Once resuspended, it will be available for further transport and subsequent redeposition in areas farther from its original source. However, wave and current energy responsible for such resuspension is highly dispersive, and will tend to spread and dilute the material over a much wider area than the original deposition zone, thus reducing the net areal concentrations.

A number of useful semi-empirical formulations for resuspension due to currents and waves can be found in the literature. Miller et al. (1977) provide a relationship between grain size in naturally consolidated sediment and threshold current speed that can be represented by a simple graph (Figure 6-1). Looking at the fine grain sizes of greatest interest in the present study (less than 63 microns), it can be seen that particle erosion will likely occur for current speeds greater than about 0.28 m/s. This is within the typical range of tidal current speeds encountered on geoduck beds. Therefore, we can conclude that resuspension of fine sediment deposited out of the plume associated with geoduck harvesting is possible, depending on the current regime at a particular site.

Surface wave energy is associated with oscillatory water movement at depth. Komar and Miller (1975) developed a technique for relating grain erosion thresholds for various grain sizes to water depth, wave height, and wave period. Their formulation can be presented in graphical form, as shown in Figures 6-2 (a and b). Figure 6-2(a) shows that for 2-second waves (frequently occurring on Puget Sound), resuspension of even fine particles on the bottom due to wave energy will be unlikely if the water depth is greater than about 4 m. Figure 6-2(b) (note the different scale for water depth) depicts the wave-

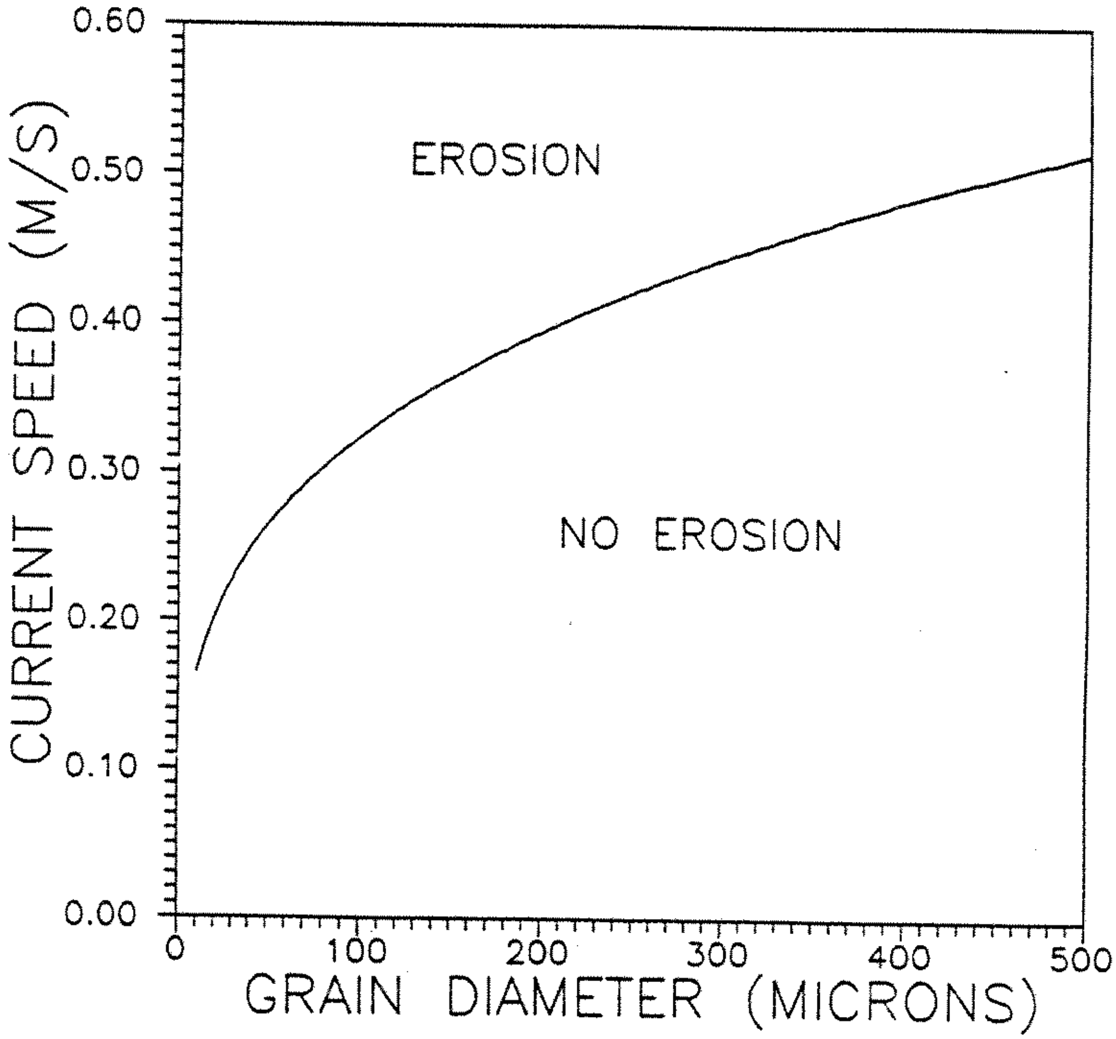
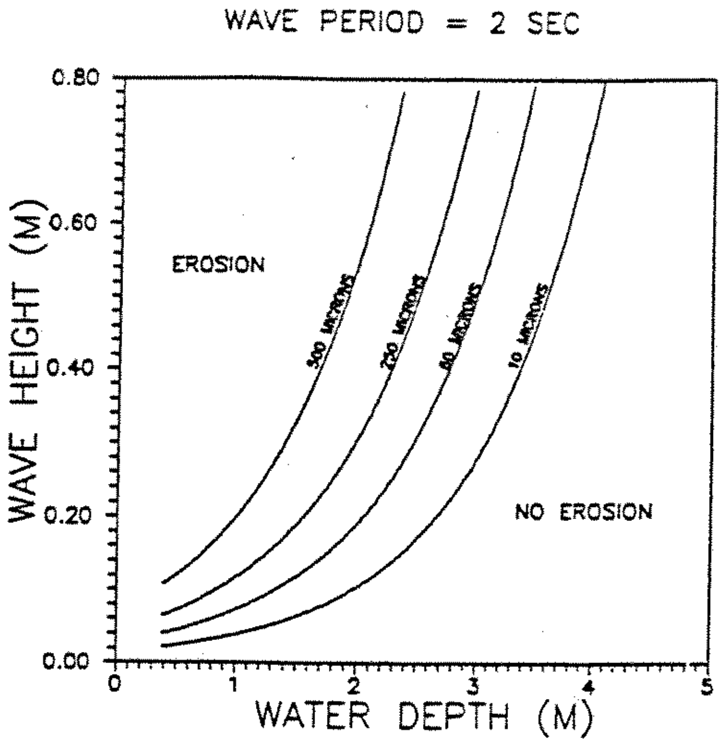


Figure 6-1. Sediment erosion threshold under unidirectional currents.

(a)



(b)

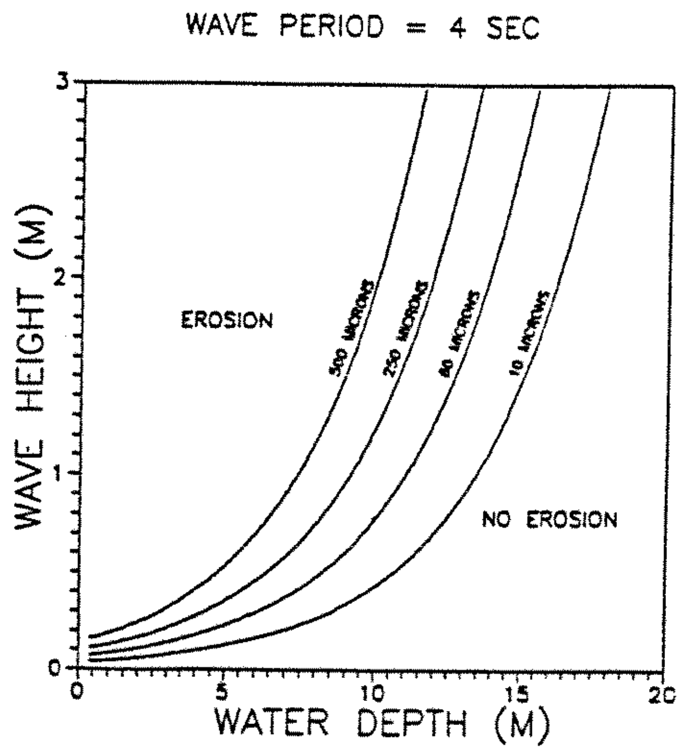


Figure 6-2. Sediment erosion threshold as a function of grain size, water depth, and wave height for wave periods of (a) 2 seconds, and (b) 4 seconds. Note the different water depth scales in the two figures.

related erosion thresholds for 4-second waves (less frequent, storm-induced waves on Puget Sound). To illustrate, for a water depth of 10 m, resuspension of fine particles will tend to occur for wave heights in excess of about 0.8 m. Depending on the location, such wave heights are possible in Puget Sound during strong wind events. As the water depth decreases, the threshold wave height for resuspension will also decrease, and thus tend to occur more frequently. As was the case with resuspension due to currents, we conclude that resuspension of unconsolidated bottom sediment due to waves is possible, and is site- and time-dependent in the Puget Sound region.

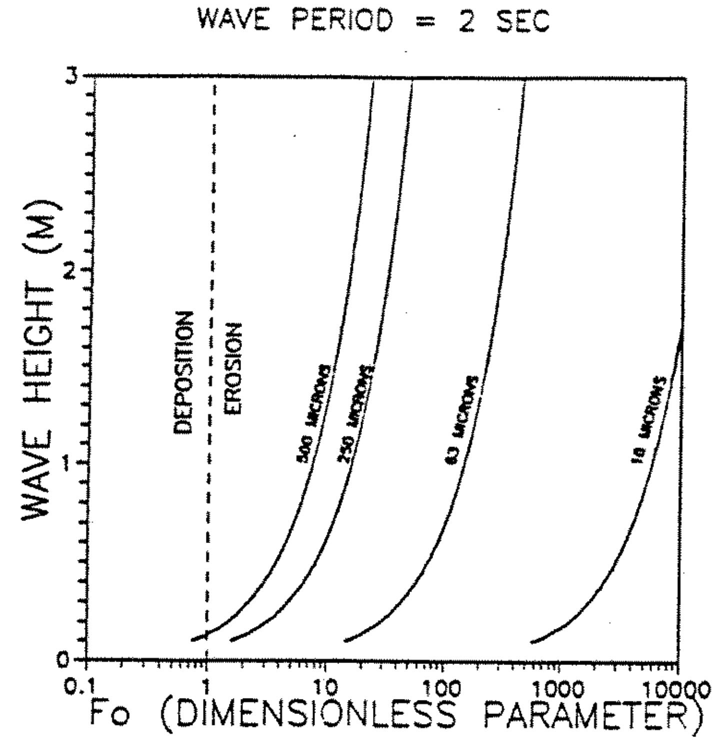
7.0 BEACH DEPOSITION AND EROSION

In Section 5.4.4, we showed that a small amount of suspended sediment resulting from geoduck harvesting may reach the shoreline and be available for deposition. In that section, we conservatively assumed that all of the available material would be deposited in the intertidal zone. In reality, the tendency for particulate matter to be deposited or eroded from beach zones is strongly dependent on the particle size and wave climate of the site. Most beaches along Puget Sound are composed of sand or gravel, suggesting that the typical wave climate is inconsistent with deposition and retention of fine sediments.

To quantify the likelihood of beach deposition, we prepared some graphs using a technique described in USACOE (1984). This technique relates wave height, wave period, and particle grain size to a dimensionless fall time parameter, called F_0, that is an indicator of the tendency for deposition or erosion to occur. Figure 7-1 (a and b) shows the results for the same wave periods (2 and 4 seconds) used previously in Figure 6-2. In these plots, the dashed vertical line corresponding to $F_0=1$ delineates the boundary between conditions under which deposition and erosion will occur. These plots illustrate a rather striking result: that for typical wave conditions in Puget Sound, deposition of fine sediment (less than 63 micron grain size) will virtually never occur if any wave energy is present. Deposition of fines on a beach will only occur in the complete absence of any wave energy. In these plots, deposition is seen only for medium and fine sand particles, and even then only under very low wave conditions.

In Section 5.4.4, our calculations based on model runs showed that the amount of material that could be deposited in the intertidal zone under worst case conditions would be extremely small. The results shown in Figure 7-1 indicate that even such insignificant deposition would be highly unlikely.

(a)



(b)

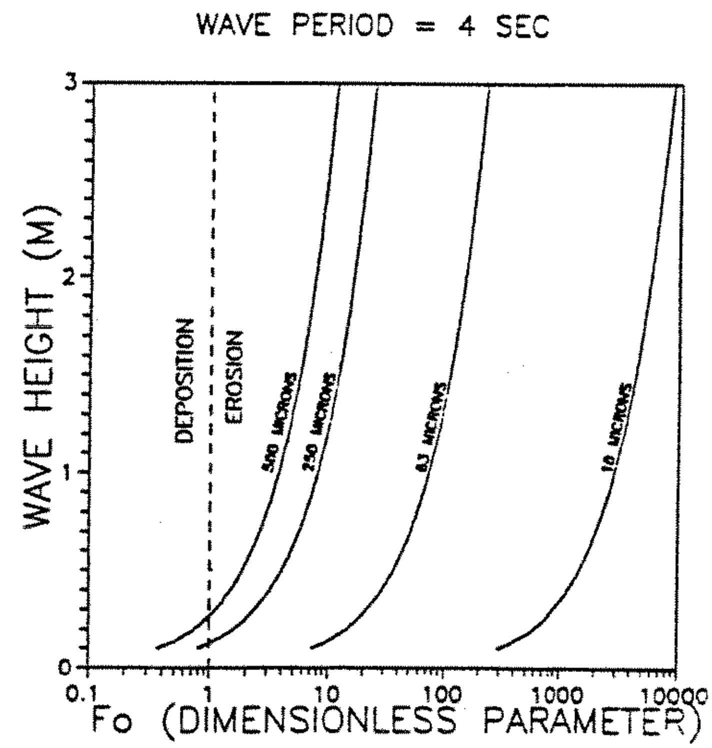


Figure 7-1. Beach deposition and erosion threshold as a function of grain size and wave height for wave periods of (a) 2 seconds, and (b) 4 seconds.

8.0 SUMMARY AND CONCLUSIONS

8.1 REVIEW OF THE EIS AND OTHER EXISTING INFORMATION

Our review of the EIS sections dealing with impacts to the physical environment identified some omissions of pertinent subject matter and some numerical inconsistencies. However, it is our finding that these deficiencies are not sufficiently serious to invalidate the overall conclusions stated in the EIS regarding physical impacts.

Very little reference material exists specifically relating to the transport and fate of suspended sediment associated with geoduck harvesting. Research on physical impacts due to hydraulic clam harvesting, while providing a worst case analogy to geoduck harvesting effects, cannot be directly applied due to the much more invasive nature of the hydraulic harvesting method. It is worth noting, however, that the research on hydraulic clam harvesting identified no significant impacts related to water quality or sedimentation.

Our focused literature search identified no pertinent references that were not cited in the EIS. Moreover, we did not find any pertinent references that have been published since the EIS was issued in 1985.

8.2 MODELING OF PLUME TRANSPORT AND FATE

We developed, tested, calibrated, and applied a numerical particle transport model (GEODUCK) to simulate the behavior of the suspended sediment plumes associated with geoduck harvesting. The model simultaneously accounts for the physical processes of advection, dispersion, and settling. The model was designed to allow the user maximum flexibility in specifying input parameters so that a wide variety of environments can be simulated. Model output includes horizontal distributions of suspended sediment concentration in the water and settled sediment concentration on the bottom.

In the model calibration step, the model was adjusted to achieve maximum agreement (significant at the 99% confidence level) between model output and actual measurements of TSS gathered during a field experiment conducted in conjunction with an actual harvesting operation.

The model results for 20-minute harvesting simulations in a 30 m x 30 m harvest area for four different current speeds showed that as the current speed increased, the suspended sediment plume lost its integrity and became segregated into a series of discrete clouds, each corresponding to the sediment released during the digging of one hole. Also, as the current speed increased, the settled sediment was displaced farther down-current from its hole, and the depositional pattern became more irregular. Local maximum and area average bottom concentrations and associated thicknesses were found to be extremely small for the 20 minute harvesting simulations. An estimate of long-term cumulative sedimentation effects, based on scaling model results to achieve typical hole density in commercial geoduck beds, yielded results that were roughly consistent with numerical estimates presented in the EIS.

Model results also indicated that some suspended material will travel as far as 200 m down-current from the harvest area, and under worst-case (albeit highly unlikely) conditions of direct onshore transport, would be available for deposition in the intertidal zone. Under the assumption that all such material would be deposited in the intertidal zone, calculations showed that the associated depositional thickness, even considering cumulative effects, would be extremely small.

8.3 SEDIMENT RESUSPENSION AND DEPOSITION

Semi-empirical techniques obtained from the literature provided the means of assessing the likelihood of resuspension of unconsolidated bottom sediment that has settled out of the plume. The results derived from these techniques indicate that resuspension of fine sediments is possible under current and wave conditions that may occur in Puget Sound. Once such material has been resuspended, it is available for further transport and subsequent deposition at greater distances from its source substrate. However, the conditions conducive to resuspension (energetic waves and currents) will further disperse and dilute the material, reducing the concentrations and depositional thicknesses.

Laboratory studies reported in the literature have shown that fine-grained marine sediment can regain most of its shear strength within 1-2 days of deposition. Presumably, within a few days of deposition, this redeposited sediment will be no more susceptible to erosion than the original substrate.

A semi-empirical technique relating sediment grain size, wave height, and wave period to the likelihood of beach deposition shows that deposition of fine suspended sediment in the intertidal zone on Puget Sound beaches is highly unlikely.

8.4 OVERALL CONCLUSION

Upon thorough consideration of existing information, field data collected during this project, plume transport modeling results, and results from semi-empirical techniques regarding resuspension and deposition, our overall conclusion is that the transport and fate of suspended sediment associated with commercial geoduck harvesting will have minimal impacts on the physical environment in the harvest tract and adjacent areas.

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